

## REP Spacecraft Design Concept Considerations

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**Abstract.** Radioisotope Electric Propulsion (REP) has the potential to provide certain advantages for outer planetary exploration involving small bodies and long term investigations for medium class missions requiring power comparable to past outer planetary exploration missions. This paper describes a preliminary conceptual design of a REP-based spacecraft where the mission of interest involves a spacecraft with a radioisotope power supply less than one kilowatt while operating for a minimum of 10-years. A key element of the REP spacecraft is to ensure sustained science return by orbiting or flying in formation with selected targets. Utilizing current/impending technological advances, REP orbiter/explorer missions may provide a valuable tool for extended scientific investigations of small bodies in the outer solar system.

# Radioisotope Electric Propulsion (REP) Spacecraft Design Concept Considerations

Daryl A. Edwards & Douglas I. Fiehler  
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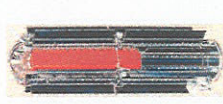
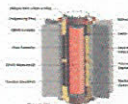
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## *REP = Radioisotope Power System and Electric Propulsion*

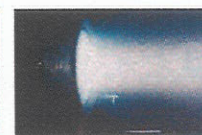
### Radioisotope Power System

- Provides Power where Solar Energy is impractical, ~ 4 AU, surface power
  - Variety of static and dynamic technologies – Advanced RPS Program
  - NASA flight heritage with RTGs  
Radioisotope Thermoelectric Generators  
including 7 interplanetary probes
    - Pioneer 10 & 11
    - Voyager 1 & 2
    - Galileo
    - Ulysses
    - Cassini
- 165 – 855 Watts (Beg. Of Mission)



### Electric Propulsion

- Provides High ISP, low thrust – high total impulse, high mission delta-V
- Variety of technologies – most current programs aimed at higher power levels (> 1 kW)
- Flight Heritage with EP as main propulsion (power from solar arrays)
  - Deep Space 1, NASA, 2300 W ion thruster
  - Hayabusa, Japan, 1150 W MW ion thrusters (3 thrusters on)
  - Smart 1, ESA, 1190 W, Hall thruster

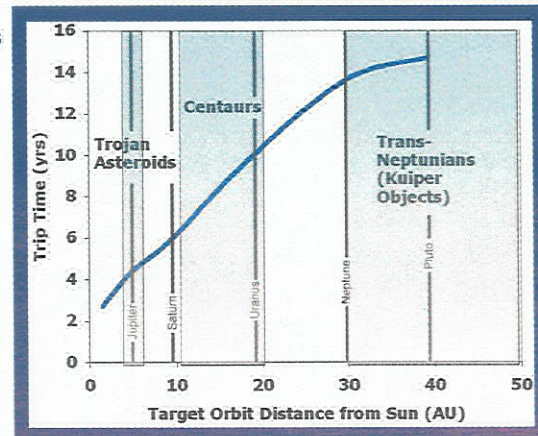


**Combined Technologies enable a new class of missions – High Delta-V, beyond Mars orbit, small spacecraft – primarily small body targets (orbit capture, co-orbit)**



## REP S/C Design Concept at a Glance

- REP provides potential mission advantages:
  - Where Solar energy is impractical
  - EP reduces propellant mass allowing larger payload mass or smaller Launch Vehicles
  - Allows orbit or co-orbit of outer Solar System bodies without need for aerocapture or gravity assist.
- The study, a conceptual point design of a spacecraft, was started based on the paper *Radioisotope Electric Propulsion for Fast Outer Planetary Orbiters*\* which provided some of the key requirements:
  - RPS capable of delivering 800 We at 8 We/kg
  - Electric Propulsion System consuming 750 We
  - Trip Time of approximately 14 years to Neptune
- Study was funded under Advanced Radioisotope Power Systems Project (formerly part of Code S) the study had these objectives:
  - Assess the feasibility of REP spacecraft
  - Identify areas requiring technology development



\* NASA/TM—2002-211893 AIAA-2002-3967 by Steven Oleson, Scott Benson, Leon Gefert, Michael Patterson, and Jeffrey Schreiber which was presented at the 38th Joint Propulsion Conference and Exhibit cosponsored by the AIAA, ASME, SAE, and ASEE Indianapolis, Indiana, July 7-10, 2002

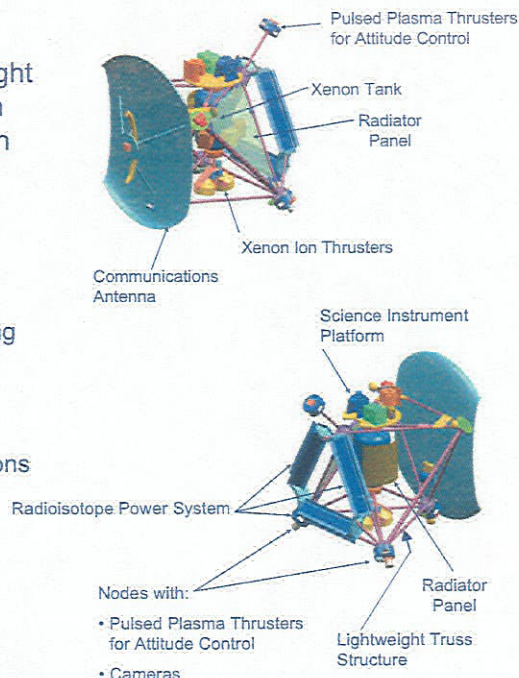
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## Outer Planetary Target Orbiter (OPTO) Spacecraft

- The study produced a conceptual design, called OPTO, intended to be a small lightweight spacecraft for outer Solar System exploration with the ability to capture at target bodies with low gravity wells.
- Some Key Features:
  - Advanced radioisotope power system achieving high specific power coupled with long duration low power electric propulsion engines
  - Pulsed Plasma Thruster (PPT) vector control attitude control system for long duration missions over 10 years
  - Maximize use of autonomous navigation
  - Light weight primary structure
  - Modular construction



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## MISSION ANALYSIS: Mission Selection

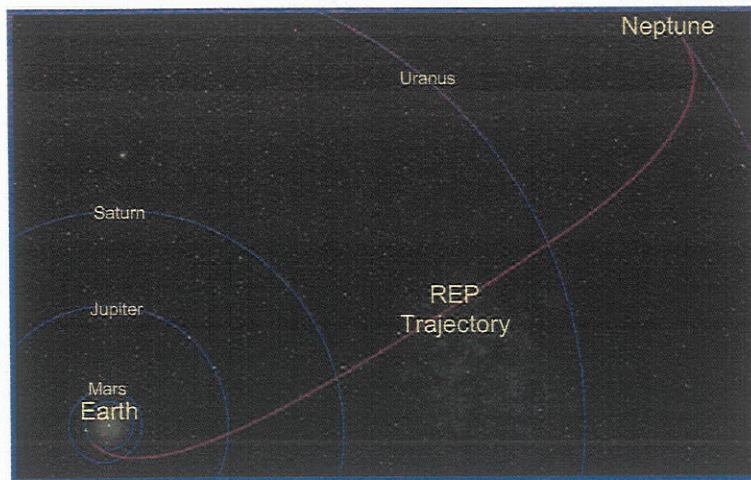
### Two Destinations Chosen to Show Range of Missions to which REP is Applicable

- Decadal Survey used to choose representative missions
  - Neptune/Trans-Neptunian Object Mission
    - Target high moon of Neptune: Nereid, or one of the many Trans-Neptunian objects
    - Spiral to Triton was deemed too costly in terms of extra trip time and extra propellant needed
  - Trojan Asteroid Orbiter
    - Target largest of Trojan Asteroids: Hektor, however other Trojan bodies would have similar mission performance
    - Possibility exists to transit to second Trojan Asteroid with proper mission planning
- The objective is to take advantage of REP's small body target capability.

### Candidate missions from the 2003-2013 Decadal Survey include:

- |  |   |
|--|---|
| • Kuiper Belt-Pluto Explorer                             | • Io Observer (Deferred)                            |
| • Jupiter Polar Orbiter with probes                      | • Ganymede Observer (Deferred)                      |
| • Comet Surface Sample Return                            | • Neptune Orbiter with Probes (Deferred)            |
| • Europa Geophysical Explorer                            | • <b>Neptune Orbiter/Triton Explorer (Deferred)</b> |
| • <b>Trojan/Centaur Reconnaissance Fly-by (Deferred)</b> | • Uranus Orbiter with Probes (Deferred)             |
| • Asteroid Rover/Sample Return (Deferred)                | • Saturn Ring Observer (Deferred)                   |

## MISSION ANALYSIS: Neptune/Trans-Neptunian Object Mission

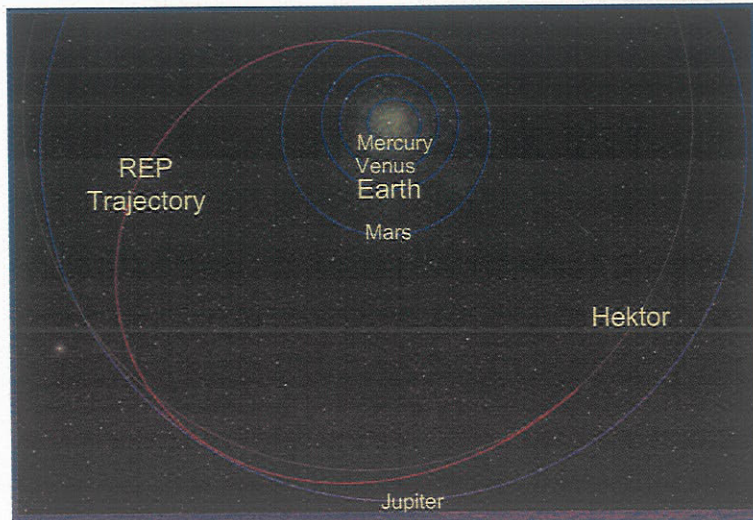


| Neptune/Trans-Neptunian Orbiter Mission |                                       |
|---|---------------------------------------|
| Trip Time                               | 14 years                              |
| Total Burn Time                         | 9.6 years                             |
| Launch Vehicle                          | Atlas V 551/Star 48                   |
| $C_3$                                   | 133.3 km <sup>2</sup> /s <sup>2</sup> |
| Launch Mass                             | 825 kg                                |
| Propellant Mass                         | 354 kg                                |
| Final Mass                              | 471 kg                                |
| EP Input Power                          | 750 W <sub>e</sub>                    |
| $I_{sp}$                                | 2533 seconds                          |
| EP $\Delta v$                           | 13.9 km/s                             |

- Neptune mission was one of the main drivers of the spacecraft design, because of long trip time.
- Mission Phases:
  - High-energy launch to Earth escape
  - Thrust until hyperbolic heliocentric escape trajectory is reached (~2.4 years)
  - Coast in escape trajectory (~4.4 years)
  - Thrust to bring spacecraft out of escape trajectory and into capture at Neptune (~7.2 years)



## MISSION ANALYSIS: Trojan Asteroid Mission



| Trojan Asteroid Orbiter Mission |                                       |
|---------------------------------|---------------------------------------|
| Trip Time                       | 4.2 years                             |
| Total Burn Time                 | 4.2 years                             |
| Launch Vehicle                  | Atlas V 551/Star 48                   |
| C <sub>3</sub>                  | 121.6 km <sup>2</sup> /s <sup>2</sup> |
| Launch Mass                     | 983 kg                                |
| Propellant Mass                 | 453 kg                                |
| Final Mass                      | 530 kg                                |
| EP Input Power                  | 750 W <sub>e</sub>                    |
| I <sub>sp</sub>                 | 1371 seconds                          |
| EP Δv                           | 8.3 km/s                              |

- Trojan Asteroid Mission chosen to demonstrate REP technology on less demanding mission with a shorter time frame
- Mission Phases:
  - High-energy launch to Earth escape
  - Thrust arc for duration of the primary trajectory (4.2 years)
  - Capture at Hektor using EP
  - Possibility of transit to secondary Trojan Asteroid target after completion of primary mission

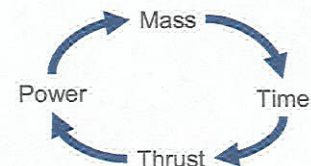
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## Study's Critical Design Requirements

- Spacecraft electrical power usage less than 1 kilowatt with maximum power to Propulsion of 750 watts.
  - Due to mass limitations and costs for RPS & Launch Vehicles
- All electrical power generated from a radioisotope power source.
  - Based on all trajectories being direct to outer planets
- Scientific data obtained over an extended period of time at target area.
  - Orbit at destination is key requirement
- Propulsion using electric propulsion engines
  - High Isp for minimizing mass
- Trip times no more than 14 years (Target dry mass of 440 kg for a Neptune mission)
  - Driven by estimated life capability of advanced RPS systems (14+ yrs)
  - Feasible mission times



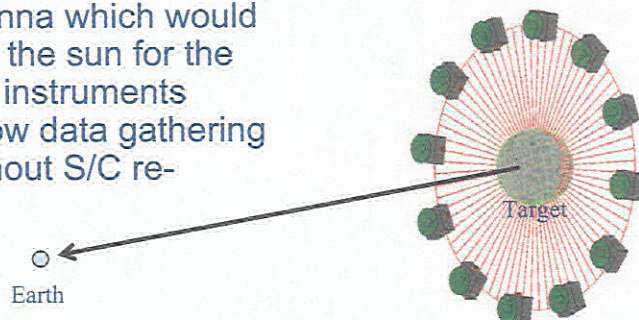


## Major Technical Design Challenges

- **LONG LIFE** – Vast distances require long transit times
  - Operate for a total mission duration of at least 14 years
  - Propulsion (EPS) operates almost continuously. Engines are expected to operate for ~10-years during a Neptune planetary system visit. Much longer than any current ion thruster has operated
  - Power carried on board since solar energy not practical for outer Solar System journeys.
  - Minimize active devices and life limited components (e.g. reaction wheels and batteries)
- **POWER UTILIZATION** – Resource utilization during transit while EPS is operating.
  - Long Trip times – plan for decreasing power of RPS
  - Long Thrust times - Minimize power needs of S/C during transit so that power is available for EPS. Affects COM, Heating, & Navigation
  - At target, EPS is shutdown and full power is available for S/C systems.
- **LOW MASS** – Incorporating low power electric thrusters, as the primary propulsion, necessitates a low mass S/C.
  - Necessary to balance the available power, thrust, and destinations
  - Impacts all subsystems and especially the spacecraft structural bus.
  - Launch Vehicle size - medium class
  - Directly related to trip time

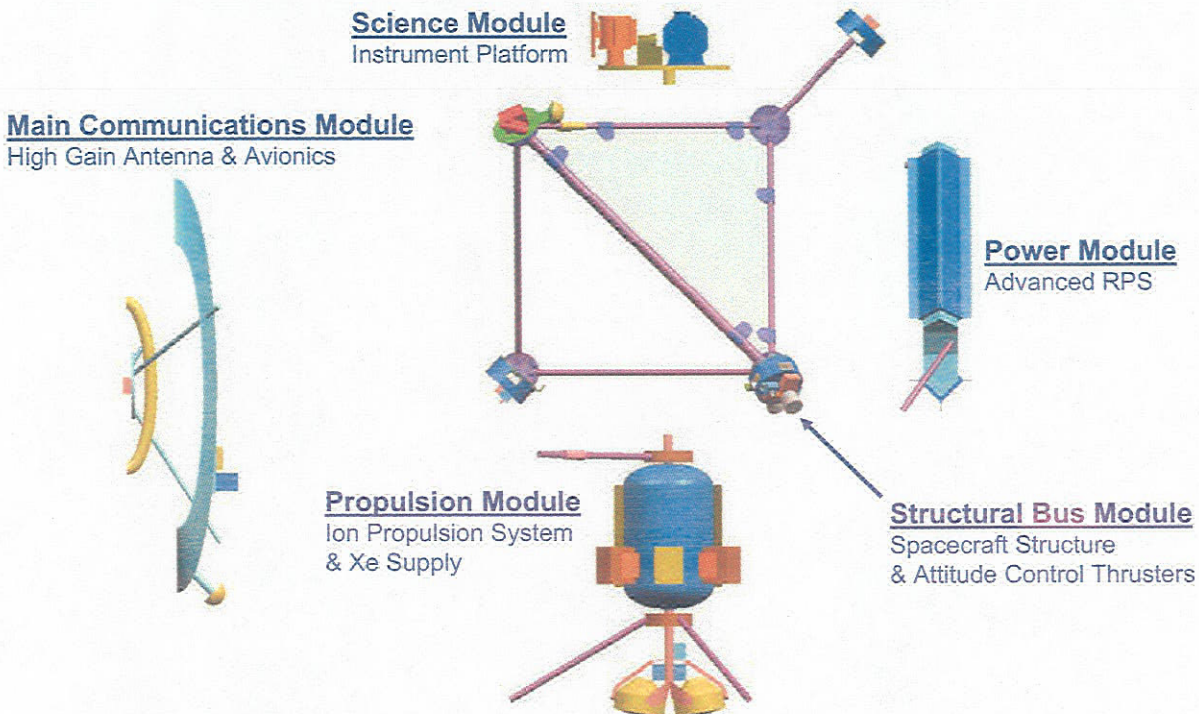
## Study's Conceptual Design - OPTO

- Overall: Modular Construction
- Structure: Truss-like (struts & nodes)
- Power: Advanced radioisotope power systems achieving high specific power.
- Propulsion: Long life low power electric propulsion engines.
- Position of hardware: RPS faced away from sun – opposite antenna which would generally face earth (and the sun for the outer planets). Scientific instruments orthogonal to HGA to allow data gathering and transmit to earth without S/C re-orientation.





## OPTO's Modular Construction



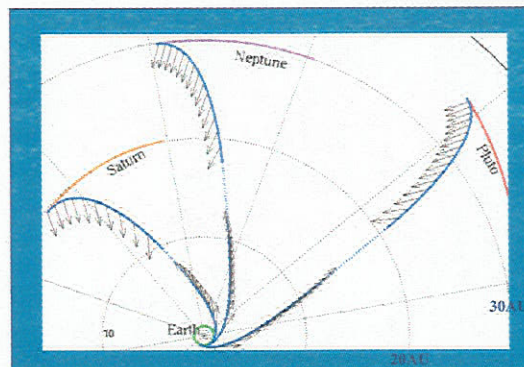
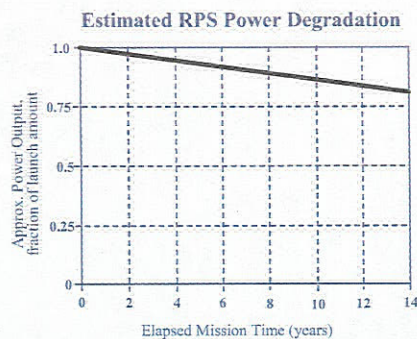
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## OPTO's Long Life Concept

- Utilize Advanced RPS with 14+ year life.
- EP thrusters:
  - Ion Engines for the longer missions with multiple thrusters used serially (3-engines for Neptune, 2-engines for Trojans)
  - Shorter missions could utilize Hall Thrusters
- ACS: All electric PPTs for long duration missions. Reaction wheels not included for > 10yr mission.
- Energy Storage: Planned for ACS and Possibly COM - Ultra-Capacitors (No batteries)



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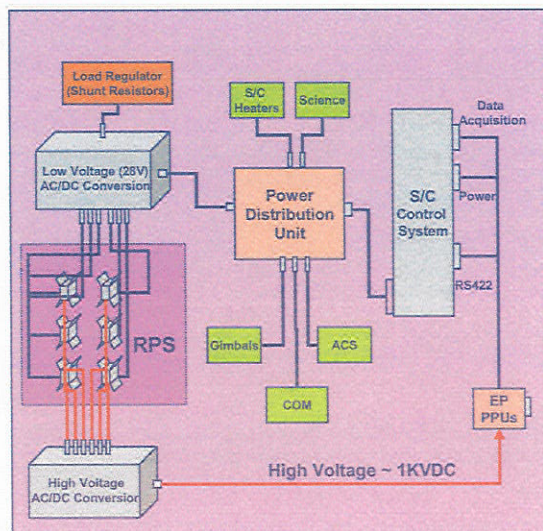
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## OPTO's Power Utilization Concept

- Initial RPS sized to handle maximum propulsion usage plus 50 watts at end of transit.
- Minimize non-propulsion electric usages during cruise
  - EP thrusters operate, one at a time, generally for duration of interplanetary transit
  - Thruster throttled down periodically to provide power for communications, navigation, & payload checkout
- Ultra Capacitors used in conjunction with PPTs and potentially COM
- Thermal – PPU Waste heat to Xenon Tank to minimize heater power during transit.
- Communications – maximize use of autonavigation and operate EPS at reduced power for communications with Earth.
- Initial concept has the RPS providing both high and low voltage power



Estimated Total Power Usage, watts

| Safe | Standby/<br>Maintenance | De-Spin | Earth<br>Search | Nominal<br>Science<br>Data<br>Collection | Communication<br>Science Data | Maneuvering<br>Orbit<br>Maintenance | Mapping | EP<br>Full<br>Power<br>Operation | EP<br>Reduced<br>Power<br>Operation |
|------|-------------------------|---------|-----------------|--|-------------------------------|-------------------------------------|---------|----------------------------------|-------------------------------------|
| 141  | 147                     | 127     | 131             | 413                                      | 413                           | 198                                 | 742     | 830                              | 730                                 |

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## OPTO's Low Mass Concept

- Advanced RPS with specific power of at least 8 We/kg – very important since it is our single largest dry mass element
- Primary Structure Bus - back to back tetrahedrons allowing for modular construction.
- Minor Contributors
  - Desire to increase power conversion efficiency through separate high voltage and low voltage systems
  - Thermal: integrate PPUs on to Xenon tank to allow direct waste heat to maintain Xenon temp.
  - ACS: small star trackers and auto-navigation

| Dry Mass Estimates                        |         |                      |
|---|---------|----------------------|
|   |         | % of S/C<br>Dry Mass |
| Science Instruments                       | 48.1 kg | 10.1                 |
| Attitude Determination & Control System   | 46.3 kg | 9.7                  |
| Command, Control, & Communication Systems | 71.3 kg | 15.0                 |
| Structures                                | 67.5 kg | 14.2                 |
| Thermal System                            | 25 kg   | 5.3                  |
| Propulsion System                         | 93.6 kg | 19.7                 |
| Power system                              | 122 kg  | 25.7                 |
| Spacecraft Dry Mass                       | 474 kg  |                      |

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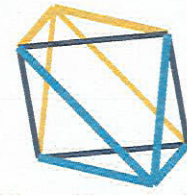
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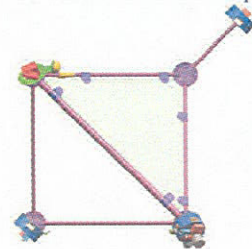


## OPTO's Structural Bus Concept

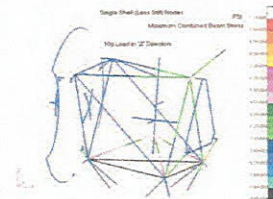
- Primary Structure is truss-like with all members directed to node centers.
- Shared base 5-node pyramids
  - Opposing Equi-lateral triangles form primary faces.
  - (10) 1.75 M 38 mm OD/ (2) 2.15 M 75 mm OD 1 mm wall ester cyanate tubes
  - tubes contain dual ethernet/ 28 volt low voltage lines in a parallel non co-linear paths
  - Remaining triangular face base/shared tube elongated to "square" spacecraft
  - elongated tube enlarged to 75 mm to house capacitor banks  $13 \times 2.5V = 32.5V$
  - Six 250 mm OD 1.67 mm wall Ti nodes
- The Propulsion Module is supported on lower tetrahedron
  - The prop module is stabilized by the upper gimbal mount bi-pod which also double as the thruster gimbal mount and science auxiliary pointing
  - which shares base equilateral triangle of the back to back pyramids which form the primary structure required to collect auxiliaries (e.g. Main Communications Module, Power Module, Propulsion Module).



3-D View of Structure Concept



Side View with Nodes And ACS Thrusters



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## OPTO Summary Characteristics

- Small Size
- Modular Construction
  - Installation of RPS at Launch Site
  - Integration & Checkout on a module basis
- Long Duration Missions
- Direct Trajectories
- Orbit small outer Solar System bodies in low gravity well locations
- The design can be adapted to other missions involving separating payloads (e.g. micro-landers, impactors, and atmospheric probes)



OPTO with Boost Stage inside 5-meter Short Fairing



Launch Vehicle

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## ***REP Concept Design Considerations***

- **Selection of Low Power Systems** – Especially those operating during EPS operation.
- **Maximize Autonavagation Capability** – Reduces use of S/C resources (ACS & Power to EPS) necessary to align S/C for communication with Earth. Also reduces ground operations and shortens trip time by minimizing EPS shutdowns.
- **Long Life High Efficiency EPS for Low Power**
  - Emphasis on low power EPS (directly drives size of RPS)
  - High total Xenon throughput for high Isp engines
  - Integration of EPS with RPS for efficient Hybrid power management
- **Long life ACS** – Reliable operation for 14+ years
- **Low-mass structures/devices** – As with all S/C, but especially with low power EPS. High impact area for design creativity.
- **Utilization of advanced power sources** - Specific power of at least 8 We/kg is extremely important. We were not capable of making the Neptune mission within 14 years at the current specific power level of ~ 4 We/kg.

